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PARTICULARS FOR WORKING OPTICAL GLASS DURING THE MANUFACTURE OF PRISM MODULES

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The possibilities of evaluating the quality of the surface working of optical glass during grinding and polishing are investigated.

Key words: optical glass, surface roughness, grinding and polishing, increase of quality.

The quality of optical components and joined surfaces is determined by, first and foremost, surface working processes. Basic factors appear here: the surface roughness of an optical component, which, when a coating is deposited, results in the appearance of thickness fluctuations of the layer and scattering of radiation; a substantial thickness of the layer destroyed by the working process on the substrate surface gives rise to fluctuations of the electric relief, which affects sorption processes, which are determining for obtaining films; in consequence, the appearance of fluctuations of the electric relief degrades the structure of the layers of the coating and the structural layer and results in fluctuations of the thickness of the growing layers; inadequate cleaning of the surface before deposition of a coating and the presence on the substrate surface of adsorbed foreign materials (contamination of the surface) likewise degrades the structure of the growing layers and results in thickness fluctuations of the layers. In addition, the presence of contamination on the substrate surface decreases coating stability with respect to operational factors.

We shall examine the possibility of evaluating the quality of the working of a substrate surface, since this is the determining factor in obtaining coatings with prescribed optical and operational properties which remain stable during operation in optical devices. First and foremost, this concerns dielectric mirrors which have the highest possible reflection coefficient and satisfy the requirement of minimal losses to scattering.

To obtain high-quality coatings that satisfy stringent operational requirements the main requirement is to have good optical surfaces with strictly prescribed properties with respect to shape and roughness. The shape of a surface is necessary for correct formation of a light beam, while minimal roughness is necessary to decreases losses to scattering and to decrease the thickness fluctuations of the layers of the coating. The latter requirement appears, at first glance, to be extraneous, since it is often thought that the surface roughness of the layers is independent of that of the substrate. However, this is not always so.

The conventional methods of working optical surfaces are described in [1]. The statistical properties of a surface cannot be represented by only a single Gaussian function [2]. But, apparently, they can be represented by a sum of several Gaussian random processes with strongly different average values and variances, where at least one these functions corresponds to a description of large defects, visible under low magnification, and corresponds to the GOST 11141–84 classification, provided that their formation can be regarded as independent of the overall picture of the appearance of roughness.

In the classification of a standard, there is no evaluation of the surface roughness itself — this is its main drawback in describing surface quality. Large defects whose dimensions exceed the thickness of the layers are practically completely inherited by a multilayer coating, while the surface roughness itself is statistically independent. As the number of layers in a coating increases, new defects appear on the surface (“spatters,” i.e., small pieces of the evaporated materials, which fly out of the evaporator simultaneously with the vapor, appear and individual grains in a layer undergo enhanced growth). These defects are inherited as the number of subsequent layers increases, which is what determines the increase of the purity class of a surface with coating according to the GOST 11141–84 classification as compared with the initial surface.

Surface roughness is regulated to some degree by GOST 2789–73, but this document determines only the upper limit

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TABLE 1.

Purity class	Area, mm^2, occupied by		Total area occupied by defects, S_{def}, mm^2	Ratio S_{def}/S_{sub}
	scratches	dots		
0 – 10	0.048	0.000207	0.048207	0.000068
0 – 20	0.078	0.0013	0.0793	0.00012
0 – 40	0.108	0.00353	0.11153	0.000158
I	0.24	0.24	0.48	0.00068
II	0.36	0.59	0.95	0.0013
III	0.6	1.18	1.78	0.0025
IV	1.2	3.50	4.70	0.0070
V	2.4	5.90	8.30	0.0117
VI	3.6	8.25	11.85	0.0168
VII	12	11.78	23.78	0.0340
VIII – $VIII_a$	12	18.84	30.84	0.0440
IX – IX_a	18	28.30	46.30	0.0660

of the roughness for a polished surface, equal to 0.025 μm. In all probability, this value of the roughness can correspond only to the roughest GOST 11141–84 surface class IX_a. For all other classes it must be much smaller. Surface roughness is most simply determined by measuring the scattering of monochromatic radiation. In such a measurement, the contribution of defects which are regulated by GOST 11141–84 is found to be small on average. This means that the visible surface defects can be completely referred to the “tail” of the normal distribution of the height of the surface asperities. In reality, according to GOST 11141–84 the area occupied by defects is distributed over purity classes in accordance with the data presented in Table 1.

The values indicated above were taken from GOST 11141–84, where upper and lower limits were introduced for the sizes of defects, i.e., defects must be no larger than a definite size for a given class; smaller defects may be completely neglected. In all probability, such limits are reasonable for visual monitoring, but these values hardly characterize the surface being described. If the number of defects which have been neglected is substantial, then scattering by the surface can increase, and an incorrect determination of the sizes of the defects which must be taken into account to determine the purity class contributes additional errors in the determination of the class.

Since the magnitude of the scattering signal is proportional to the coefficient of reflection from the surface, it follows from the data in the Table 1 that the average magnitude of the scattering by the largest surface defects is small for surfaces belonging to high classes and large for the surfaces of quite rough classes. The presence of defects will give local scattering outliers at the defect points. These outliers are easily detected when a surface is scanned. In other words, the purity class of a surface can be easily determined according to the scattering of monochromatic radiation.

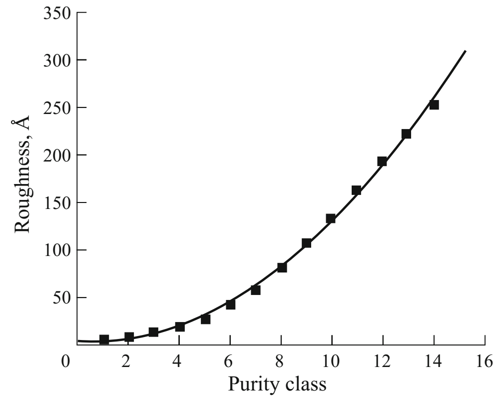

Fig. 1. Average roughness of polished surfaces as a function of the purity class.

We have performed measurements of the total scattering by a large number of K-8 glass and quartz substrates belonging to different purity classes. All substrates were well polished, but in a number of cases the powders were not normalized according to the grain size. An increase of the grain-size variance of a powder resulted in the formation of defects on the surface of an optical part, which is what caused the appearance of variance of the parts over the purity class. The average heights of the asperities in the relief (obtained for a large number of substrates with a large number of measurement points on each one) are presented in Fig. 1. For convenience in constructing the plot the purity classes in this figure are renumbered. The first class includes classes 0 – 10, the second class 0 – 20, and so forth. The outliers due to scattering by visible defects were discarded when the average values were determined. The results presented in Fig. 1 show that as the number of the purity class increases, the surface roughness increases exponentially. Scattering increases with increasing surface roughness.

The most important, most often used, and probably the most often incorrectly decreased statistical parameter of a surface is its rms roughness δ, which can be determined as follows [3]. The profile is measured along a line of length L. This line determines the average level of the surface in a manner so that the “areas” bounded by the profile, which lie above and below this line, turn out to be equal to one another.

The variations of the heights of the asperities are measured perpendicular to the line L.

Now let us consider N discrete points which are separated by the same distance from one another along a line L and at which measurements are performed. The rms roughness is determined as the square root of the average value of the distances z_j from the points of the surface to the average level of the surface. In mathematical form this looks like this:

$$\delta = \sqrt{\frac{1}{N}\sum_{j=1}^{N} z_j^2}\,.$$

Thus, to determine the rms roughness of the surface it is necessary to calculate the average level of the surface. If the

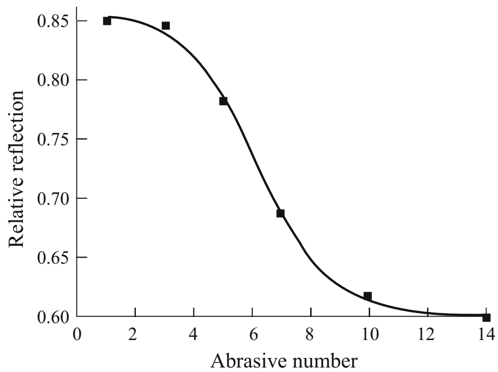

Fig. 2. Variation of the relative specular reflection coefficient of glass as a function of the abrasive number for grinding on a brass tool.

surface is wavy, i.e., it contains roughness components with large spatial wavelengths, then the computed values of δ will depend, in general, on the length L used in the calculation. If the points used in the calculation are the result of averaging the height variations over a small area on the surface, then the rms value δ will depend on the size of the area. For these reasons, the rms roughness of any particular surface changes and depends on the following factors:

the length L of the profile (i.e., the maximum spatial length of the surface wave);

the area of the surface over which the result is averaged at each measured point (i.e., on the resolution along the horizontal); and,

the distance between the measured points (i.e., the sampling — discretization — interval).

The same surface can have different values of the “rms roughness” depending on the instrument used to perform the measurements. Moreover, since the spatial wavelengths present in the profile with length L are sometimes bounded quantities less than $L/2$ (or, in other words, by spatial frequencies greater than $L/2$), we sometimes cannot obtain the “true” value of the surface roughness, containing information about all spatial wavelengths of the surface from zero to infinity. In most cases, the statistical characteristics calculated from the profilometric measurements are used to obtain information about the light scattered from the surface. In this connection, the interesting range of spatial wavelengths extends approximately from $\lambda/2$ to 150λ. However, to investigate production processes during working of the surfaces by a diamond cutter it may be necessary to cover the range of spatial wavelengths from several tenths of a micron to several millimeters (in order to see the results of the interaction of the tool with the blank and evaluate the effect of the rigidity of the support, rectilinearity, and temperature variations).

When the roughness is calculated from the measurements of the light scattering, the value of the rms surface wave is also confined within a strip. This value will depend on the wavelength of the light used for the measurements and on the range of angles at which the scattered light is collected.

High-precision optical surfaces are obtained by successive grinding and polishing of glass or crystal blanks. As a result of performing these processes, microscopic cut-outs in the form of small cavities appear on the surface of the substrate while a so-called damaged (cracked and deformed) layer appears inside the substrate material (to a certain depth). The depth at which the deformed layer is located depends on the main size of the grains and on the load on a grain of the abrasive material and is several-fold greater than the thickness of the outer (mat) layer. For K-8 glass it is estimated to be 2.8 μm on a finished polished section. The outer (relief) layer consists of a rough surface with randomly distributed protrusions and depressions.

It should be noted that the grinding and polishing operations differ according to how the abrasive acts on the material of the blank. In the case of grinding, the main process is cutting while immediately during polishing, aside from cutting, plastic deformation of existing protrusions and depressions occurs according to Bailby’s theory [4], and therefore virtually no cracks are formed. If the surface grinding is done correctly, then the cracked and relief layers decrease as the abrasive number decreases. In this case, the specular reflection coefficient of the surface increases and reaches a limiting value depending on the conditions under which the process is conducted (Fig. 2) [1].

The sharp difference in the evenness of a ground and polished surface of glass led to the hypothesis that the mechanism of both of these processes is different and led to the development of different theories of the polishing process.

Comparing the relations presented above between the magnitude of the damage on the surface being worked and the physical – mechanical properties of the materials, the working tool, the size and hardness of the grains used for grinding and polishing powders it is evident that the materials used for polishing must impart immeasurably finer structure to the worked surface under identical operating conditions. It would seem natural that sharp difference of the properties of the materials used for grinding and polishing glass should result in a completely different surface structure of the polished glass. Whether it is qualitatively different, for example, from finely ground glass and whether conditions making it possible to determine a smooth transition from a ground surface to a polished surface with gradually decreasing microasperities can be created are very important questions for understanding the essence of the polishing process.

It is completely obvious from the experiments that ultrafine mat surfaces with a gradual transition from finely ground to a polished surface can be obtained. An ultrafine mat surface structure retains the usual structure of the relief layer of ground glass, only its irregularities are so small that they give negligible scattering of light; according to the amount of reflected light such a surface is close to a surface which has been polished using the usual method.

When polishing brittle materials, such as glass and many crystals, partial removal of the material occurs, making it possible to decrease the size of the cracked layer by means of polishing. However, even the absence of a cracked layer on polished parts says nothing about the absence of altered deformed layers, and the deformed layers arise in a natural manner with polishing and are manifested in the optical properties of the substrate as additional absorption and scattering of the reflected and transmitted radiation. For high-precision engineering, optical parts are fabricated only by deep grinding and polishing, i.e., by means of grinding and polishing with strictly regulated transitions from coarse- to fine-grain powders. The powders must be carefully washed, i.e., the size variance of the grains in each fraction must be reduced to a minimum. Substrates prepared by this method are characterized by a minimum depth of the deformed layer, complete absence of a cracked layer, and a good form of the surface. The form of the surface is determined at the grinding stage, and if the correct tool has been chosen, then the surface is distorted very little during polishing. The polishing process itself is quite prolonged and takes up most of the time in the overall process of obtaining a surface. The roughness of the surface decreases exponentially with increasing polishing time (Fig. 3) [1].

Ionic working (surface etching) is also performed to obtain surfaces with a minimally deformed layer. In addition, ionic polishing makes it possible to change the form of the surface somewhat or create a new surface, which is completely impossible to do by mechanical methods. It should be noted that ionic polishing leaves the magnitude of the surface roughness practically unchanged, but it can smooth large defects somewhat. Such working is mainly used to obtain a prescribed form for the surface to decrease aberrations in the instrument (obtain a conformal surface) and to activate the surface during deposition of interference coatings.

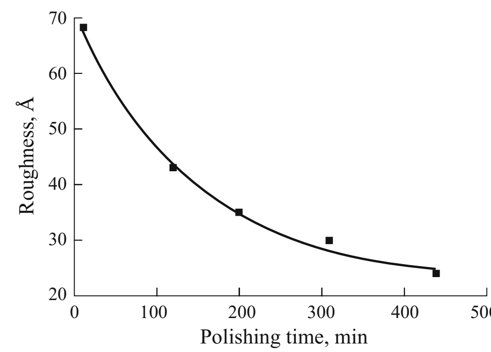

Fig. 3. Decrease of the roughness of the surface being polished as a function of the polishing time.

In summary, high-precision optical surfaces can be obtained by adhering strictly to the sequence of grinding and polishing glass or crystal blanks. If this sequence is disrupted or some transitions to the grinding stage are missed, it is impossible to correct the defects by increasing the working time using finer powder.

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